GN&C Trades for Touch-and-Go Sampling at Small Bodies

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Touch-and-Go (TAG) Sample Collection

- A descent of the spacecraft to the surface, …
- Followed by a brief (few-second) sampling contact with surface material, …
- And an immediate ascent of the spacecraft from the surface.

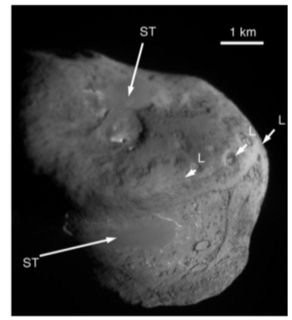
TAG differs from both (a) planetary Entry, Descent and Landing (EDL) and (b) capture of a uncontrolled satellite.

Attribute	TAG	Mars EDL	Satellite Capture
Duration	~6-24 hrs	5-8 minutes	Varied
Velocity Range	cm/s to m/s	Km/s to rest	cm/s to m/s
Reversibility	Passive and Active Aborts	None	Passive and Active Aborts
Repeatability	Yes	No	Yes
Ascent	Part of TAG activity	None	Departure not concurrent
Environmental Variability	Unknown surface compliance	Unknown winds, density; surface hazards	Target shape, structural properties well known
Testing in Relevant Environment?	No end-to-end facility exists; limited simulation of zero-g, dust environments.	No end-to-end facility exists; some field testing.	Some facilities exist on ground; ISS/SPHERES in orbit.

- The key technical challenge is to master the spacecraft-sampling hardware-surface interaction.

Representative TAG Targets

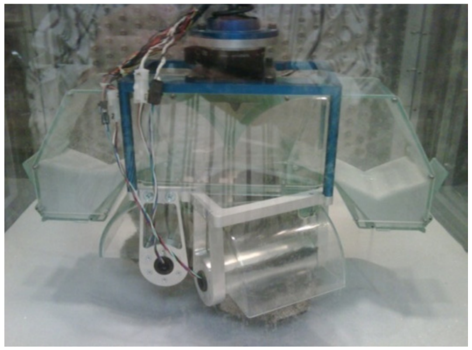
- Deimos
  - Staging Orbits
  - Well-known GM
  - Repeatable Lighting, Orientation
  - Smooth Terrain (at observed scales)
  - Post-TAG return to Staging Orbit



- Tempel 1
  - Staging Region
  - Wider uncertainty on GM, rotation dynamics
  - Possible smooth terrain
  - Outgassing, lifted particles

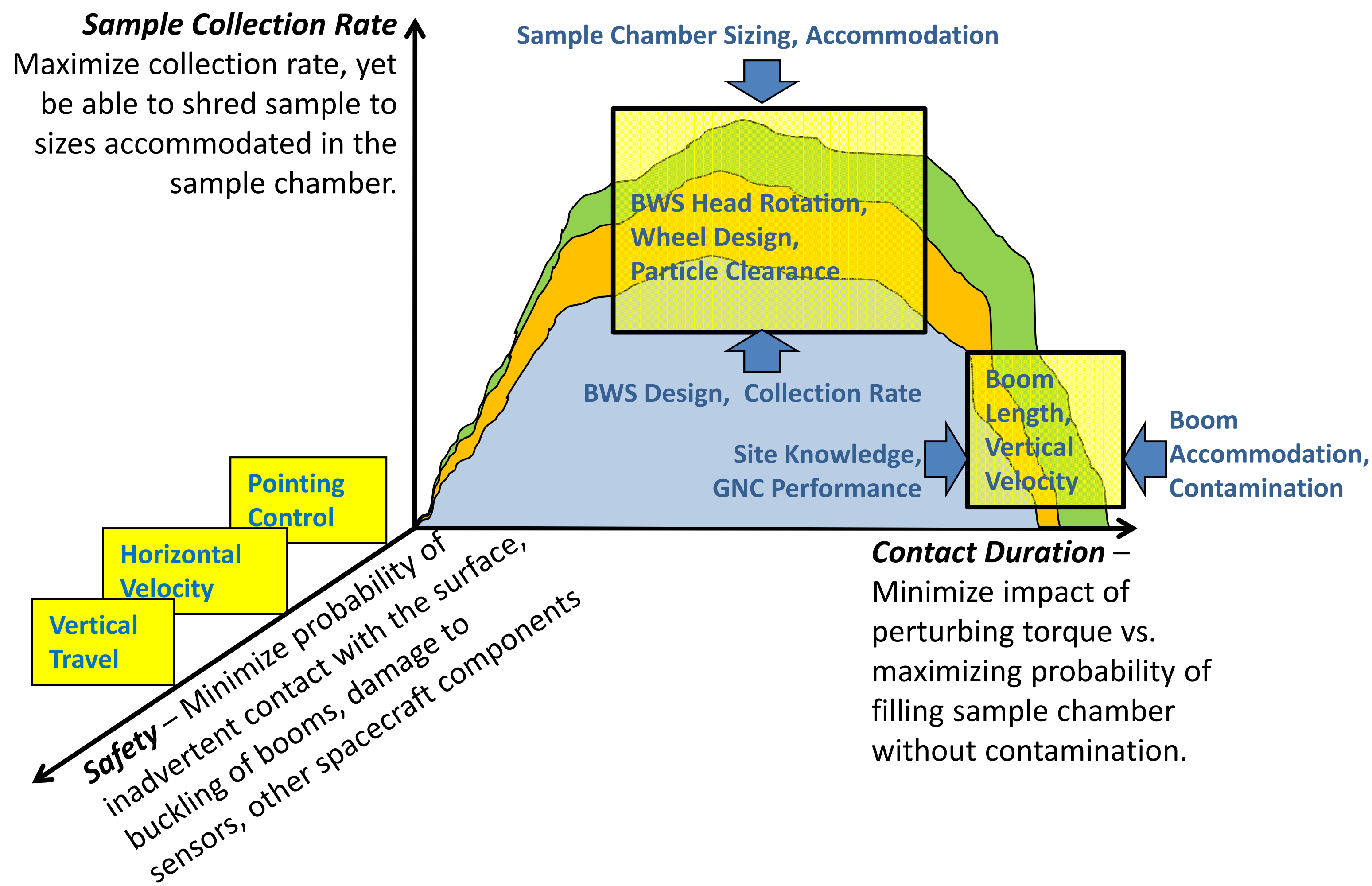
TAG Functions, Assumptions, Representative Design Principles

- *Functional Requirements* in critical sequence
  – Navigate the spacecraft from a Staging region to a pre-determined Sampling area on the small body surface.
  – Deliver operating sample collection devices to the Sampling area within appropriate orientation, force, velocity, and temperature bounds.
  – Detect spacecraft contact with the surface.
  – Ascend to a safe distance.
  – Protect the spacecraft while in close proximity to the surface.



- *Design Assumptions*
  – Primary Sample Collection Device: Brush Wheel Sampler
- *Design Principles*
  – Spacecraft design shall have positive margins to (contact duration, rotation and rotation rate) in the presence of the peak expected terrain roughness and perturbing torques corresponding to surface compliance variability, over the contact duration.
  – During the TAG phase of the mission, the spacecraft operating modes achievable from termination of the on-board sequences shall result in a safe condition for the TAG event.
  – The spacecraft configuration for TAG shall, with a minimum of active control, achieve and maintain a predictable and safe attitude and distance from the surface, starting from any orientation and control mode, in the presence of gravity (and outgassing) forces.

TAG Design Drivers



Maximizing Collection Rate

- BWS Orientation at Contact - What is the expected orientation of the BWS ‘brush-axle plane’ with respect to the surface at contact?
  - Attitude control error
  - Shape modeling error
  - Navigation Slope error
  - Navigation Delivery error
  - Surface Roughness (least understood contribution)
- Recommendation to put large margin on ability to collect samples in different orientations.
- BWS Design Issues –
  - Sizing of the sample collection device,
  - ‘Shredding’ capability of the wheel design,
  - Clearances between the wheels and the entrance to the sample collection chamber.
- Out of these trades comes a recommended operation range of forces to which the spacecraft must apply through the boom system and BWS to the surface.

Managing Contact Duration

- Ensure that the contact duration is sufficient to collect the expected quantity of sample without risking spacecraft safety.
- Abort Timer - Given altimeter biases, slower approach velocities raise the risk that the abort timer, if needed, will go off when the spacecraft is much closer to the surface than expected.
- Selecting the sensor/technique for determining the spacecraft distance on TAG terminal approach is important for managing the knowledge of when contact begins.
  - In the Deimos case, where there are known smooth terrain regions and the body mass and dust processes lead to reasonable packing of material, altimetry methods are in favor.
  - In the Tempel 1 case, given the expected low-density packing structures of material, a more direct geometric measurement from optical data (e.g. stereo odometry) mitigates the risk of not knowing what the effective surface is as sensed at microwave frequencies or visible light.
- Boom Scaling – The stroke of the spacecraft (the maximum amount of descent of the bus after contact) is proportional to the descent velocity. The length of the boom assembly, together with the descent velocity, should allow for extra margin in the stroke distance.
  - The upper limit on rigid boom sizing is the accommodation of the assembly on the spacecraft.
  - BI-STEM booms can be deployed for distances much longer than the characteristic size of the spacecraft bus.
  - Very long tethers (10s of meters) to decouple the end-effector dynamics from the spacecraft dynamics during the surface contact phase
- Contact Detection –
  - Load cell near BWS
  - Boom joint measurements
  - Detection thresholds

Protecting the Spacecraft

- <u>Horizontal Velocity at Contact</u>
  - Residual horizontal velocity at contact from maneuver execution errors.
  - Drop Maneuver size.
  - Optical landmark correlation and/or velocimetry can be used to null out the horizontal velocity on final descent.
  - By keeping the horizontal velocity at a factor of 3-4 below the vertical velocity, the direction of the normal force through the BWS is still within its operational range.
- <u>Attitude and Translational Control During Contact</u>
  - Flight system must handle the duties of ascent and attitude control in the presence of an unknown perturbing torque.
  - Maximum allowable attitude perturbation limit.
  - Initial perturbing torque
    - Deterministic Vertical Motion -
    - Residual Horizontal Motion -
    - Induced Horizontal Motion –
- <u>Fault Detection and Response</u>
  - Prior to the Drop Maneuver
  - After the start of the Drop Maneuver
  - Disable reboots, execute the Ascent Maneuver

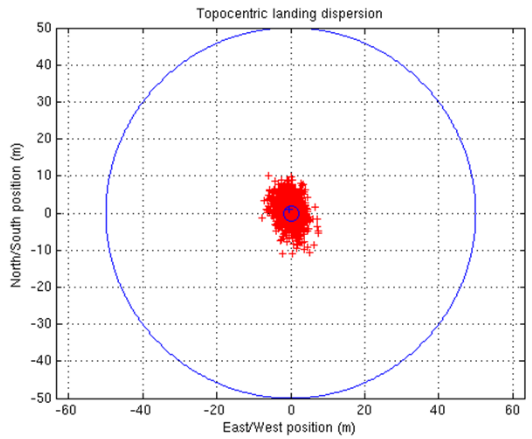
Ascent Control

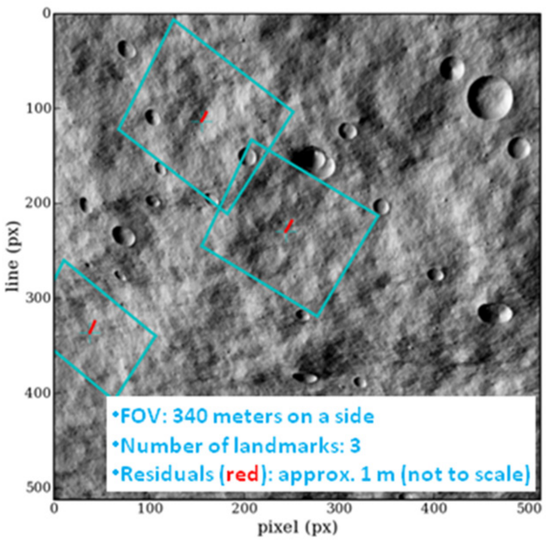
- Develop sampling perturbation torque envelope
- Attitude rate, attitude, translation time limits
- Efficacy of momentum wheels
- Propsed ascent control approach proposed (Blackmore) divides the maneuver into two stages.
- In general, the stages can be executed in either order; order and durations are design parameters.
- If there is sufficient latitude available to command the appropriate force magnitude in the stage to correct attitude, it may be possible to eliminate the other stage entirely.

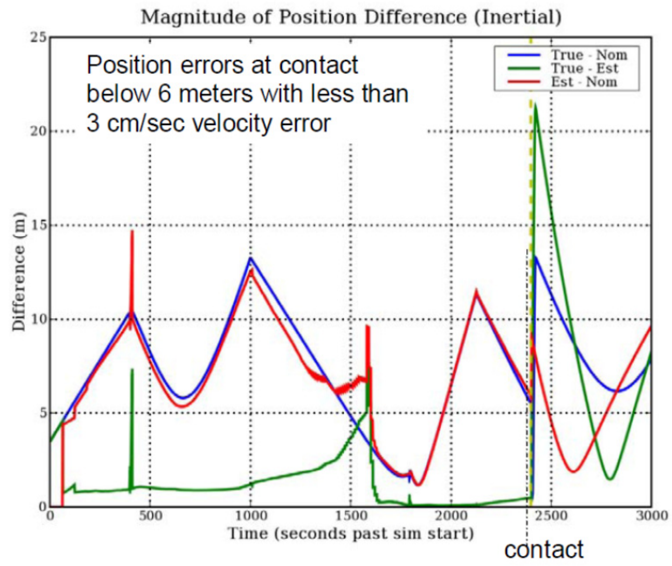
Stage Priority	Translational Controller Role	Attitude Controller Role	Thruster Manager Role
Reverse ΔV	Command the desired reversal direction in the spacecraft body frame.	Command zero torque.	Command thrusters to maximize the force along the desired reversal direction without imparting any torque.
Correct Attitude	Command the desired reversal direction (and potentially the magnitude of the force in that direction) in the spacecraft body frame.	Command a control torque to correct the attitude errors due to contact.	Command thrusters to provide the desired torque as closely as possible while maximizing the force along the desired reversal direction (prioritizing torque).

TAG Evaluation

- TAG 'Test-as-you-fly' (flight system, sample system, small body environment, dust, etc.) is a significant challenge.
- Simulations and tests emphasizing the flight dynamics or structural dynamics of TAG can be coordinated so as to begin to confirm spacecraft performance at TAG by quantifying performance and margin against safety limits.
- <u>Navigation Simulations</u> – 3DOF+ simulations confirm spacecraft surface delivery performance.
- <u>Navigation Autonomy Simulations</u> –AutoGNC software testbed simulates its operation on a flight system. The simulations test AutoGNC capabilities and performance including spacecraft GNC autonomy, Terrain-Relative Navigation (TRN), real-time image-based feedback control, and 6 DOF TAG control at contact.

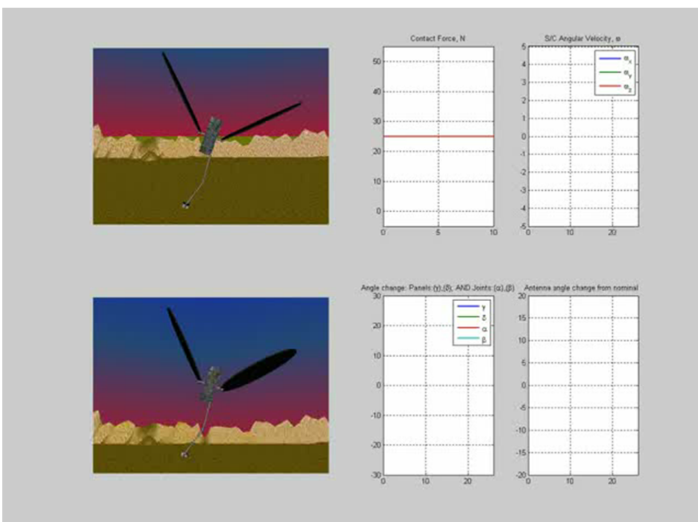


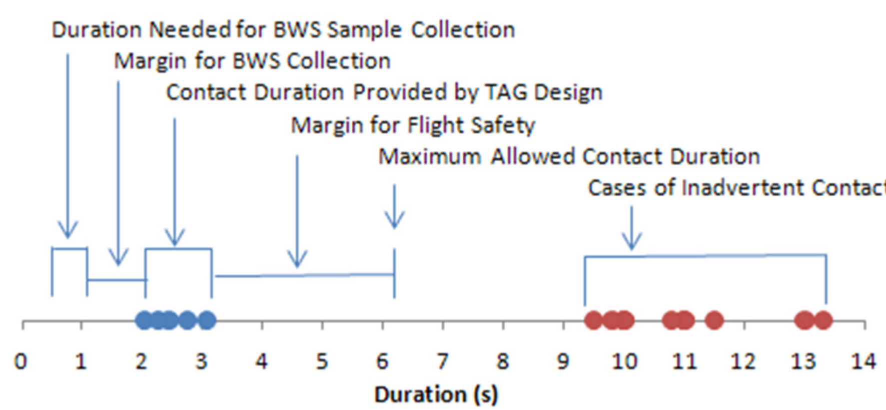




TAG Evaluation (cont.)

- Spacecraft/Sampler/Surface Simulations – JPL simulation capability (G-TAG) models the functionality of the flight system, the control-structure interaction with the sampler-boom system and solar panels, maneuver execution errors, and the sampler interaction with the surface. Panel joints and the small-body surface are modeled with spring-damper models, and the boom joints are modeled with nonlinear dampers.
- With these simulations, the control algorithm response throughout contact can be studied and the performance under various conditions (surface compliance, slope, etc.) evaluated in a Monte Carlo sense to get overall performance metrics. One performance metric is the 'effective contact duration' during which the BWS is operating under appropriate force levels; another is the 'spacecraft survival limit,' the duration that the spacecraft can remain in safe contact with the surface without inadvertent contact.





TAG Evaluation (cont.)

- <u>Sample Collection (Hardware)</u> – 2 and 3-brush versions of BWS prototypes with sample collection chambers have been built and tested on a variety of sample material types.
- Parabolic flights
- Vacuum (see right).
- Sample collection rates and force profiles were measured.
- From these measurements contact force models (including tangential friction and shear, and vertical stiffness and damping) for G-TAG simulations were created and validated.

- <u>Sample Collection Simulations (Software)</u> – Adams multi-body dynamics simulations were used to model the structural dynamics of the sample collection system (booms and BWS) with the surface.
- Testing confirmed the BWS prototype test results and demonstrated that the BWS brushes were able to shred and collect the surface material at the measured rates.
- The testing also showed that these rates could be achieved on uneven slopes (up to 30 degrees) and for surface material strengths beyond the expected range by a factor of 4.
- Simulations also helped confirm the appropriate number of degrees of freedom and joint locations in the boom design

In summary, all the simulation capabilities are of high fidelity, and each element generates results that can be cross-checked against adjacent elements. These capabilities also provide ancillary information (e.g. attitude, attitude rates, thruster usage) to confirm spacecraft safety and quantifiable robustness against the unknown qualities of the small-body surface.

Other Considerations, Conclusions

- Sample Verification
  - There are several concepts - context cameras, radiating through the sample chamber, measuring changes in capacitance, etc.
  - Sample collection chamber mounted to a load cell.
  - Maneuvers pre- and post-TAG to solve for 'spring constant' and collected mass.
  - Simulations show that the mass can be confirmed to 20-25 g 1-sigma for a 300g sample.
  - TAG ascent maneuver could also be used; additional modeling would be required.
- Other TAG Considerations
  - Role of Ground in the Loop
  - Available Target Knowledge
  - Sensor Redundancy vs. Protection
  - Overall Reliability
- Conclusions
  - TAG is a unique activity – its energy and momentum management issues differ from the violent deceleration themes of EDL and the mechanically-arresting aspect of spacecraft capture.
  - These differences are evident in the descriptions of the overall activity, the driving requirements, and the range of small body environments.
  - Time and orientation management are key metrics for the design and its evaluation.
  - While flight path and attitude knowledge and control are coupled in TAG, with sufficient authority the ascent control strategy can be made to keep those two aspects separate during the most important function – departing the surface.
  - Much proficiency and verification can be accrued with connected hardware and software simulation capabilities.